

Naval Submarine Medical Research Laboratory

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**THE SUBMARINE ATMOSPHERE ULTRAFINE
PARTICLE STUDY**

by

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RESULTS: The median UFP count within the submarine control room fell from 1,967 to 992 particles/cm³ over the 20-day period. A similar decrease in UFP numbers from 10,441 to 4,502 particles/cm³ was recorded within the maneuvering room.

CONCLUSIONS: Measurement of UFPs onboard a submarine reveals a decrease in UFP numbers over the course of a 20-day period. This suggests that either UFPs are not produced in large numbers within the closed submarine environment, or that the existing atmosphere purification systems are efficient at removing any UFPs that are produced. It should also be noted that the UFP levels measured within the living spaces of the submarine were lower than those measured within a house, and even within the engineering compartments, UFP levels were significantly lower than levels measured in a number of European cities.


THE SUBMARINE ATMOSPHERE ULTRAFINE PARTICLE STUDY

BENTON PJ, SLAVIN DE, DINARDI SR, BURNSIDE D, WOOLRICH R

Naval Submarine Medical Research Laboratory
Report #1242

Research Work Unit Nos. 5708, 50504

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A handwritten signature in black ink, appearing to read "J. Daniel", with a stylized flourish at the end.

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TABLE OF CONTENTS

SUMMARY.....	1
ABSTRACT	3
BACKGROUND.....	4
OBJECTIVE.....	6
METHODS.....	6
RESULTS.....	9
DISCUSSION.....	15
CONCLUSIONS.....	17
REFERENCES	18

SUMMARY

Epidemiological studies of the health effects of air pollution have revealed that exposure to airborne particulate matter, in particular fine and ultra fine particles, is associated with an increase in both respiratory and cardiovascular morbidity and mortality (1, 2, 3). Airborne particulates range in size from 0.001 μm to 100 μm and arise from a wide variety of sources. These include 'natural' sources, such as sea salt nuclei, volcanic activity and wind driven erosion of rock, as well as man made sources, primarily the products of combustion. Particles below 0.1 μm are referred to as ultrafine particles (UFP) and result from combustion, sea salt nuclei and the end products of chemical reactions that take place within the atmosphere, including those that involve ozone and volatile organic compounds (VOCs). Slightly larger particles of between 0.1 μm to 2.5 μm are referred to as fine particles and include fumes and dust. Particles of above 2.5 μm and less than 10 μm are known as coarse particles and include fungal spores, pollen and particles generated by wind erosion and volcanic activity (4).

The submarine atmosphere is a 'complex chemical engine' in which a wide variety of chemical compounds, including ozone, VOCs and the products of combustion (diesel engines, decomposition of lubricants, the byproducts of cooking and tobacco smoke) are present. Diesel powered submarines have to surface at frequent intervals to run diesel engines to recharge their batteries. While on the surface any atmospheric contaminants that have accumulated are flushed from the submarine by the 'fresh' surface air that is used to ventilate the submarine. Nuclear powered submarines however are capable of remaining submerged for prolonged periods of time and rely upon complex filter systems to ensure continued air purity. One such system is the 'vent fog' precipitator (VFP) that uses an electrostatic charge to remove particulate matter from the submarine atmosphere. Although the VFP appears to be effective in reducing particulate load, its method of operation is such that electrical arcing can occur within the VFP. This may not only produce ozone but might also have the effect of converting coarse and/or fine particles to UFPs.

Prior to this study, no attempt had been made to measure the numbers of UFPs in a submarine atmosphere. This report details the techniques used to measure UFPs onboard the submarine the USS WYOMING, using a portable UFP monitor (the TSI P-TRAKTM Ultra Fine Particle Counter Model 8525, TSI, Incorporated, St. Paul, MN), and compares the findings with UFP measurements carried out in a number of indoor office and residential areas on shore. The results indicate that UFP levels onboard operational submarines are low and comparable to, or less than, levels detected within office and residential spaces ashore. The UFP levels detected within the control room of the USS WYOMING (mean 1,687 particles/cm³, SD 1,911) were lower than the levels measured within a suburban house (mean 2,370 particles/cm³, SD 3,940) (5). Even within the submarine machinery space, the median value of UFPs detected at sea of 4,502 particles/cm³ was half that recorded in Aberdeen City Centre (10,241 particles/cm³); (6) and less than 3% the level recorded close to a busy Interstate in the USA (160,000 particles/cm³) (7). The explanation for such low levels of UFPs is probably a

combination of few sources of UFPs onboard, and the high efficiency of the atmosphere purification systems installed onboard modern nuclear powered submarines.

ADMINISTRATIVE INFORMATION

This work was conducted under Work Units 5708 and 50504, entitled: Submarine Atmosphere Health Assessment Program (Submarine Ultrafine Particle Study). The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official or reflecting the views of the Department of the Navy, Department of Defense, nor the United States Government. This research has been conducted in compliance with all applicable Federal Regulations governing the Protection of Human Subjects in Research IRB Protocol #NSMRL 2001.0002. This Technical Report was approved on 9 November 2006, and designated as NSMRL Technical Report #TR-1242.

ABSTRACT

BACKGROUND: Ultrafine particles (UFPs) are recognized as being associated with an increase in respiratory and cardiovascular morbidity and mortality. The submarine atmosphere is a closed environment in which it is known that potential sources of UFPs are present, especially within the engineering spaces. Prior to this study no attempt had been made to determine whether UFPs are also present in the submarine atmosphere.

AIM: To determine whether UFPs are present in significant numbers within the submarine atmosphere.

METHODS: A portable UFP monitor (the TSI P-TRAK™ Ultra Fine Particle Counter Model 8525, TSI, Incorporated, St Paul, MN) was used to measure UFP levels onboard a submarine and a shore side office. Measurements were taken in a number of submarine compartments while alongside, shortly after proceeding to sea and after 20 days at sea.

RESULTS: The median UFP count within the submarine control room fell from 1,967 to 992 particles/cm³ over the 20-day period. A similar decrease in UFP numbers from 10,441 to 4,502 particles/cm³ was recorded within the maneuvering room.

CONCLUSIONS: Measurement of UFPs onboard a submarine reveals a decrease in UFP numbers over the course of a 20-day period. This suggests that either UFPs are not produced in large numbers within the closed submarine environment, or that the existing atmosphere purification systems are efficient at removing any UFPs that are produced. It should also be noted that the UFP levels measured within the living spaces of the submarine were lower than those measured within a house, and even within the engineering compartments, UFP levels were significantly lower than levels measured in a number of European cities.

BACKGROUND

Environmental air pollution has been associated with an increase in both respiratory and cardiovascular morbidity and mortality (1, 2, 3). Pollutants include both gaseous pollutants (SO_2 , NO_2 , CO) and particulate matter. When considering the effects of inhaled particulates on the human respiratory system, it is important to assess the size of the particles, as particle size will determine the distance the particle penetrates the respiratory system and hence where it will be deposited. Particles are not perfect spheres, and in order to place them in groups that reflect their movement and deposition characteristics, inhaled particles are categorized by their aerodynamic equivalent diameter. The aerodynamic equivalent diameter (d_{ac}) of a particle is defined as the diameter of a sphere of unit density that has the same terminal settling velocity in air as the particle in question. Particles less than $10\mu\text{m}$ are categorized as “coarse” particles, those less than $2.5\mu\text{m}$ “fine” particles, and particles less than $0.1\mu\text{m}$ are known as “ultrafine” particles or UFP.

Airborne particles range in size from $0.001\mu\text{m}$ to $100\mu\text{m}$ and arise from a wide variety of sources. They include ‘natural’ sources, such as sea salt nuclei, volcanic activity and wind driven erosion of rock, as well as man made sources, primarily the products of combustion and the end products of chemical reactions that take place within the atmosphere, including those ozone and volatile organic compounds (VOCs). The larger particles, those in excess of $10\mu\text{m}$, are removed from the inhaled air as it passes through the upper respiratory tract. These large particles, traveling at the relatively high air velocities encountered within the upper respiratory tract, have difficulty negotiating the convoluted system of nasal turbinates and impact upon the moist mucosa from where they are excreted by sneezing or the swallowing of nasal secretions. Only particles less than $10\mu\text{m}$ are able to pass into the tracheobronchial tree.

Air velocity within the tracheobronchial tree falls from approximately 200cm/sec in the trachea to $1\text{-}2\text{ cm/sec}$ in the terminal bronchioles. At the high velocities present in the relatively large airways of the proximal sections of the tracheobronchial tree, inertial impaction of particles can occur, especially where airways divide, with sedimentation and diffusion playing little role in particle capture. Within the distal portions of the tracheobronchial tree, the much lower air velocities encountered favor sedimentation and diffusion as mechanisms by which particulates are removed. Of these two mechanisms, sedimentation is the most important as despite the terminal bronchioles having a small diameter, the distances involved are still too great for diffusion to be a significant mechanism. The epithelial lining of the bronchial tree is ciliated and particles impacting upon the mucous covered cilia are removed from the bronchial tree by the coordinated beating of these cilia. This mucociliary escalator is capable of removing particles from the tracheobronchial tree at a rate of 16mm/min . The combination of inertial impaction in the larger proximal airways, and sedimentation in the distal airways combined with the mucociliary escalator, effectively filters and removes particles of between $10\mu\text{m}$ and $1\mu\text{m}$, preventing them from reaching the most distal part of the bronchial tree, the alveoli.

Only particles less than 1µm are able to enter the alveoli. Air velocity within the alveoli is less than 0.1cm/sec and hence sedimentation and diffusion are the predominant mechanisms of deposition. Very small particles, those less than 0.1µm, are primarily deposited onto the alveolar walls by diffusion and from there may pass into the pulmonary circulation with resultant systemic effects.

Although the size and number of particles has been recognized as an important indicator of penetration and effect for over 40 years: until recently it has not been practicable to measure *particle number count concentration* (*particles/cm³*). Measurement of *particle mass concentration* (µg/m³) however is relatively simple, only requiring measurement of the mass of particles collected on an inert filter media, and it is for this reason that most current ambient air quality standards are based upon this form of measurement. The terms PM10 and PM2.5 refer to the mass concentrations of particles with diameters smaller than 10µm or 2.5µm respectively. PM10 is a measure of the particle mass that can be inhaled while PM2.5 provides a rough estimate of the particle mass capable of reaching the distal sections of the pulmonary tree. Although easy to measure, particle mass may not be as important as particle number, and hence particle surface area, when considering the adverse health effects of very small particles such as UFP (3, 6). The toxicity of UFPs appears to be influenced by both the composition of the particle and its surface chemistry (8).

The relative contribution of UFP number to surface area as calculated by Oberdorster (9) is illustrated in Table 1. These figures clearly illustrate the deficiencies inherent in using a particle mass concentration as it can be seen that a single 2.5µm particle may have the same mass as nearly twenty thousand 0.1µm particles of the same density, yet only 4% of the surface area.

Table 1. Number and surface area of particles of unit density of different sizes at an assumed particle mass concentration of 10µg/m³

Particle Diameter (µm)	Particle Number Count (number/cm³)	Particle Surface Area (µm²/ cm³)
0.02	2,400,000	3,016
0.1	19,100	600
0.5	153	120
1.0	19	60
2.5	1.2	24

After deposition within the alveoli, UFP appear to escape uptake by the alveolar macrophages and are able to pass into pulmonary interstitial tissues where in some animals they have been noted to initiate an inflammatory response. Animal studies (10) have also revealed that inhaled UFP are capable of translocating via the circulatory system to other organs, with UFP detectable in the liver within 30 minutes of exposure. UFP have also been shown to translocate along the olfactory nerve to the olfactory bulb

(11). This evidence suggests that inhaled UFP are capable of entering the body and passing to multiple organ systems where it has been hypothesized they may initiate adverse health effects.

Within the submarine environment there are a variety of potential sources of UFP. These include cooking processes, tobacco smoking, heat decomposition of lubricants and occasional diesel engine operation. In addition it is possible that the high voltage electrostatic “vent fog” precipitators (VFP) that are designed to remove oil mist from the engineering spaces (the oil mist resulting from the lubrication of high speed machinery) may actually generate UFP. If significant numbers of UFP were present in the submarine environment then this would be of great concern especially as the submariner, unlike the industrial worker who is only exposed for 7-8 hours per day, 5 days per week, would be exposed to the UFP for a continuous period of up to 90 days. Prior to this study no attempt had been made to measure UFP in a submarine environment.

OBJECTIVE

To sample air for UFP in a variety of submarine compartments, both prior to deployment and after the submarine had been underway for 20 days, and compare UFP levels with readings taken using identical equipment in shore side office spaces.

METHODS

Equipment

Ultrafine particle numbers were measured using a P-TRAK™ Ultra Fine Particle Counter Model 8525 manufactured by TSI Incorporated, St Paul, MN. The P-TRAK™ (Fig 1) is a small hand held portable battery powered device measuring 27cm x 14cm x 14cm and weighs only 1.7kg.



Figure 1. P-TRAK™ Ultra Fine Particle Counter Model 8525

A small built-in pump draws particles into the P-TRAK™ where they pass through a saturator tube. Here they mix with an alcohol vapor (isopropyl alcohol). This mixture of alcohol and particles then passes to a condenser tube where the alcohol condenses onto the particles forming a larger droplet. Moving into the final chamber these droplets pass through a focused laser beam. As each droplet passes through the laser beam, the laser is scattered and the resulting flash of light is counted by a photo-detector. Each flash of light equates to a single particle and as the volume of air passing through the P-TRAK™ is known, an accurate measurement of particles per cubic centimeter can be made. The process of ‘growing’ the particles into larger droplets is essential as the particles alone would be too small to scatter sufficient laser light and be detected.

The P-TRAK™ is capable of measuring particles between 0.02 to 1µm at a concentration of up to 500,000 particles/cm³. The duration of monitoring is limited to approximately 6 hours due to battery life (6 AA alkaline cells) and the capacity of the isopropyl alcohol reservoir. Measurements are taken at 1-minute intervals and stored by the P-TRAK™ for later download and analysis.

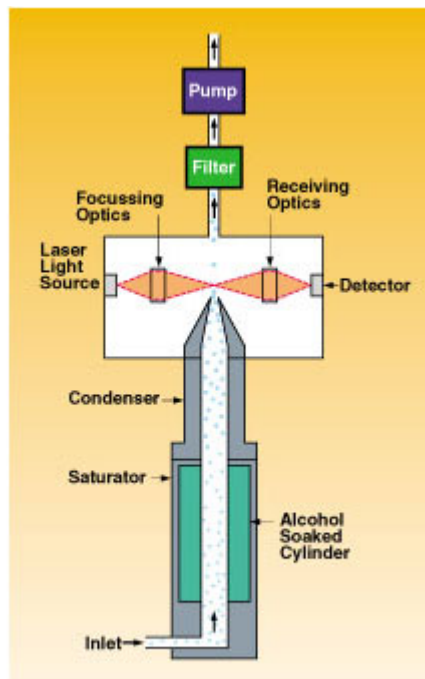


Figure 2. Cutaway diagram of P-TRAK™ Ultra Fine Particle Counter Model 8525

Measurement sites

P-TRAK™ Ultra Fine Particle Counter Model 8525 was used to measure UFP concentrations in a number of compartments onboard the submarine. Recordings were taken before the submarine sailed, during which time multiple hatches were open and the submarine was being ventilated with fresh air. Further recordings were taken shortly

after the submarine was underway and dived and finally after a period of 20 days submerged. Submarine compartments monitored included maneuvering, the control room, galley, crews berthing, auxiliary machine room and the crew's lounge.

Additional recordings were taken using the same P-TRAK™ unit placed in a large open office at the Naval Submarine Medical Research Laboratory (NSMRL). This office is air-conditioned and is usually occupied by 3 to 4 individuals.

Measurement protocol

At each site where measurements were to be taken, the P-TRAK™ was placed in a secure location where it would not interfere with submarine operation and where it was protected from inadvertent interference by crewmembers. The P-TRAK™ was fitted with new batteries before each measurement session and the isopropyl alcohol reservoir filled to capacity. This enabled the P-TRAK™ to record data for at least 6 hours. At the end of each measurement period, data from the P-TRAK™ was downloaded onto a laptop for future analysis.

RESULTS

The UFP concentrations measured both at NSMRL and onboard the USS WYOMING are given in Table 1. Figures 3 to 14 are graphs detailing the minute-by-minute UFP numbers for each location. The results obtained reveal a wide range of values from a maximum of 60,354 particles/cm³ recorded in maneuvering to a minimum of only 58 particles/cm³ in the crews berthing area. Measurements taken in maneuvering and the control room show a decrease in UFP numbers over the 20 day underway period with the median value falling from 5,750 to 4,502 particles/cm³ in maneuvering and from 1,967 to 992 particles/cm³ in the control room.

**Table 1 Ultrafine Particle measurements recorded onboard
USS WYOMING and at NSMRL**

Sample Site	Sample time	Sample date	UFP count (particles per cm ³)		
			minimum	maximum	MEDIAN
NSMRL Office	1040 to 2155	29 Aug 2001	2	19,180	4,756
Maneuvering	2242 to 0357	in port	4,827	13,090	10,441
	1040 to 1220	at sea	4,146	6,158	5,750
	0606 to 1114	at sea +20 days	600	60,345	4,502
Control Room	1217 to 1733	at sea	146	22,440	1,967
	1014 to 1653	at sea +20 days	283	10,212	992
Galley	1819 to 2219	in port	389	15,906	2,692
	1822 to 2336	at sea	436	25,596	946
Crews berthing	0414 to 0954	in port	58	312	161
AMR	1229 to 1353	at sea	667	2,943	948
Crews Lounge	0004 to 0524	at sea	351	2,454	608

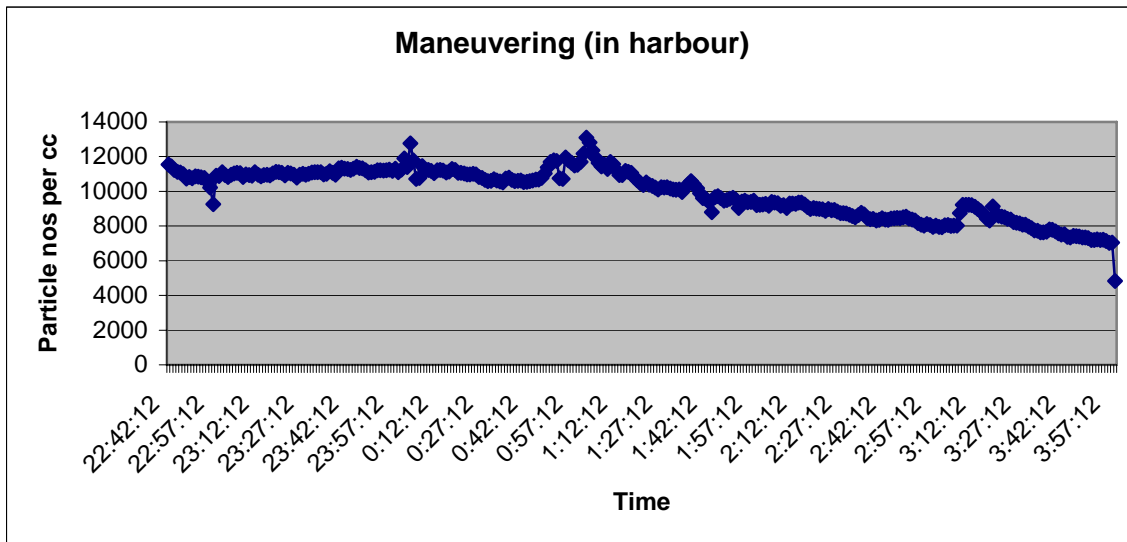


Figure 3. UFP measurements taken in the maneuvering room while in port

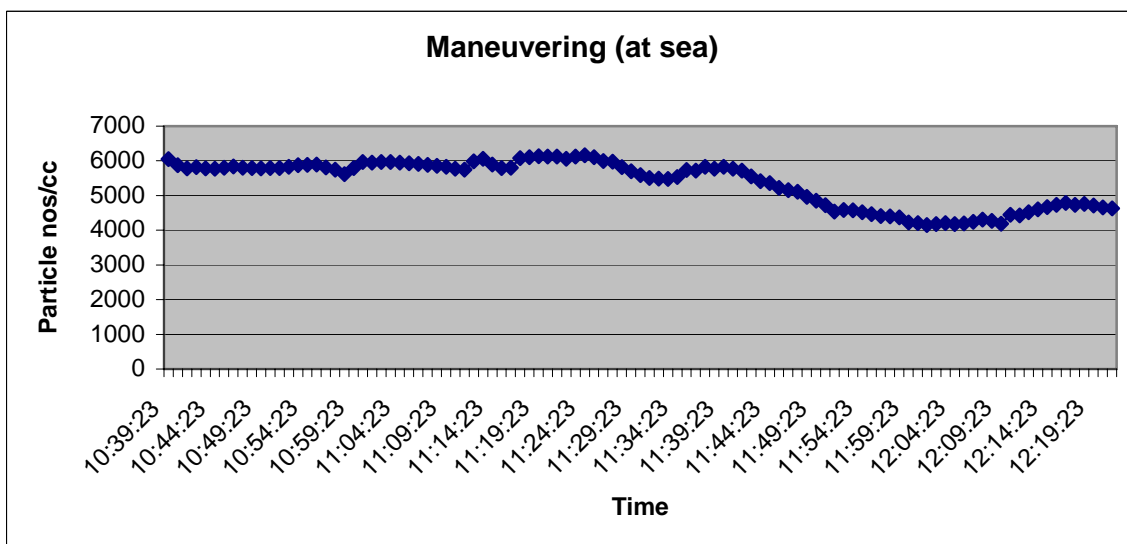


Figure 4. UFP measurements taken in the maneuvering room while at sea

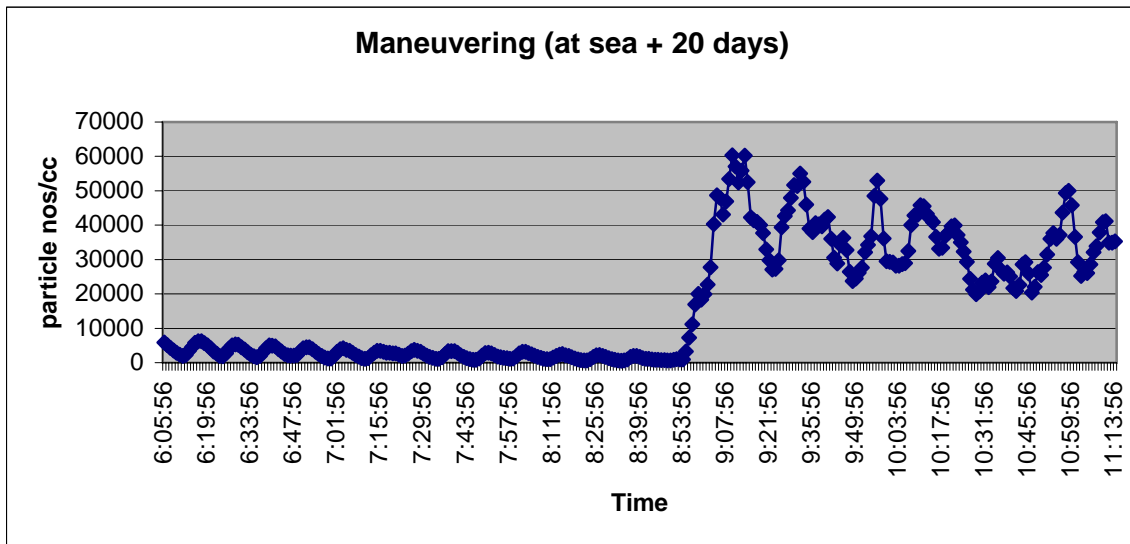


Figure 5. UFP measurements taken in the maneuvering room while at sea + 20 days

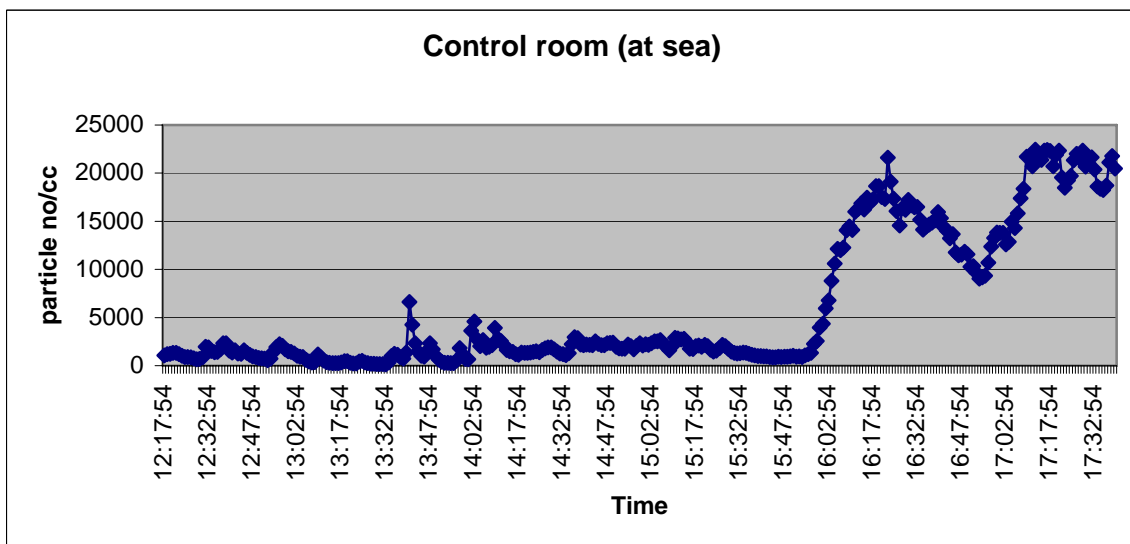


Figure 6. UFP measurements taken in the control room while at sea

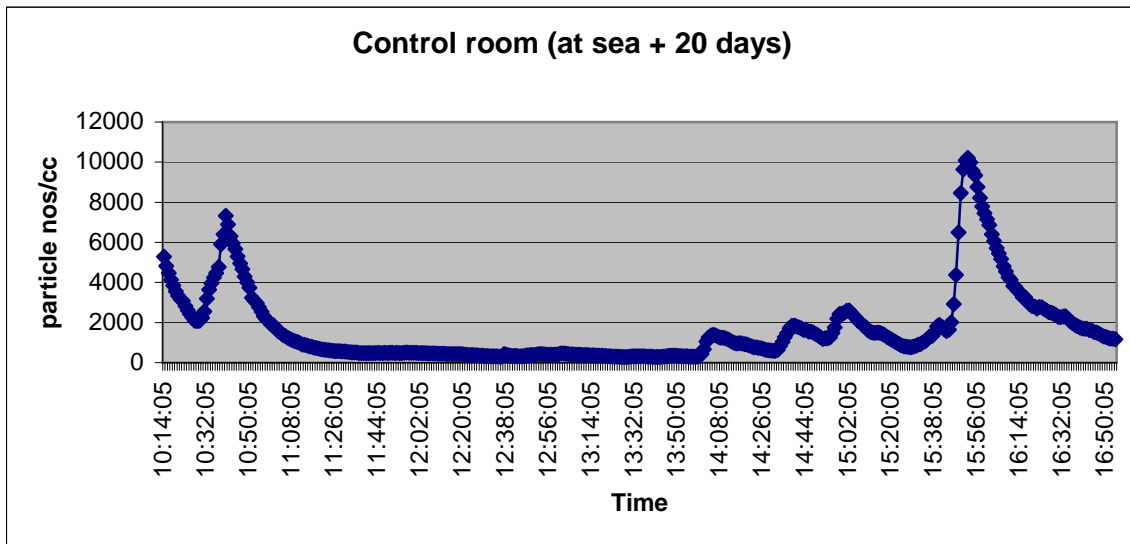


Figure 7. UFP measurements taken in the control room while at sea + 20 days

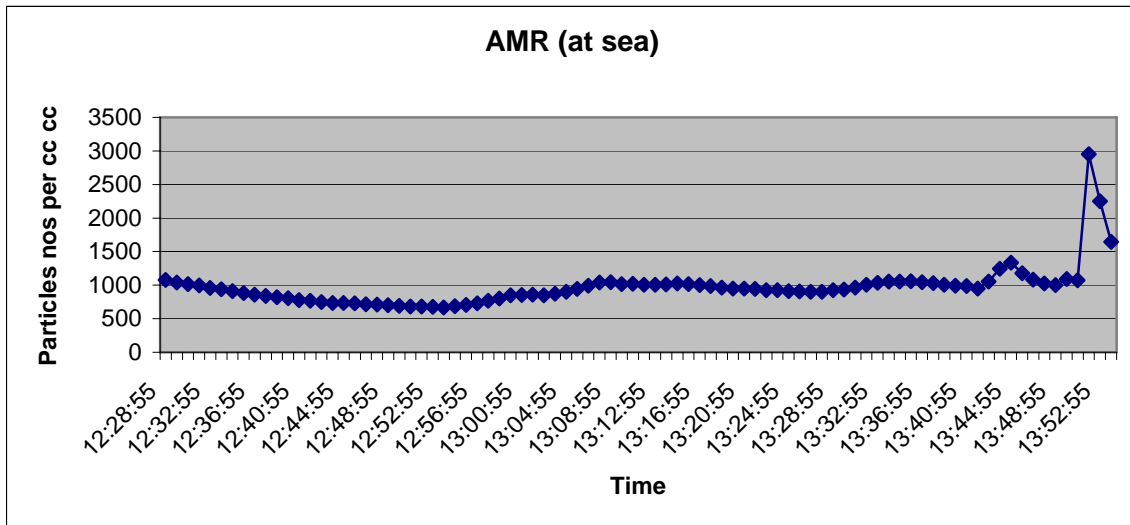


Figure 8. UFP measurements taken in the AMR while at sea

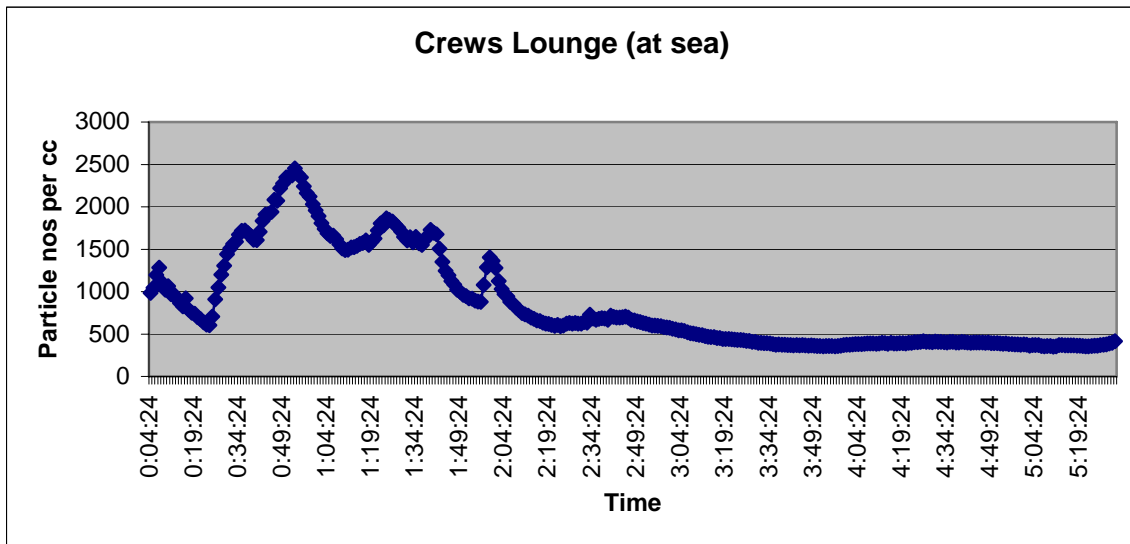


Figure 9. UFP measurements taken in the crews lounge while at sea

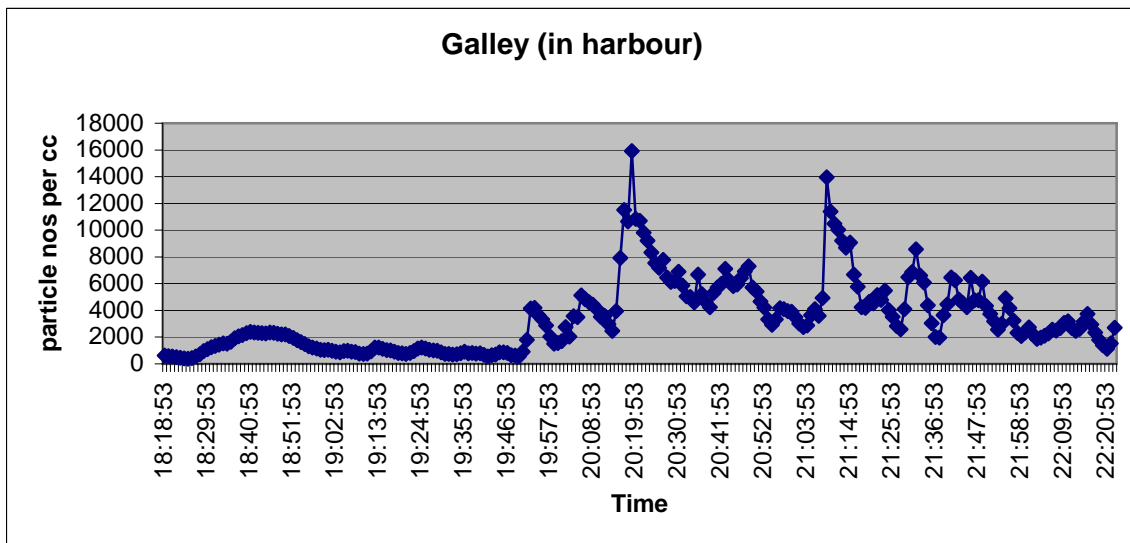


Figure 10. UFP measurements taken in the galley while in port

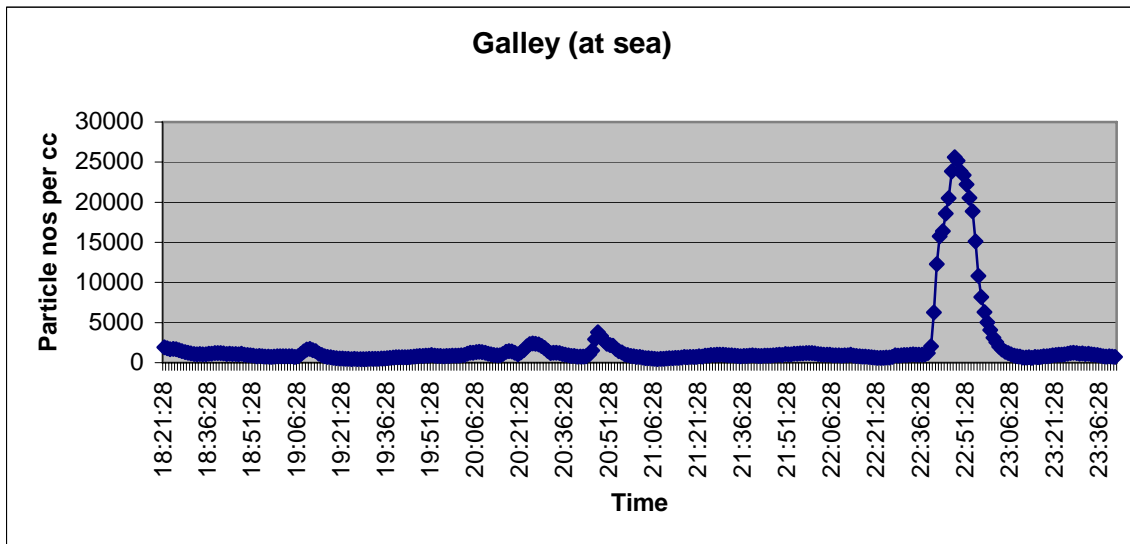


Figure 11. UFP measurements taken in the galley while at sea

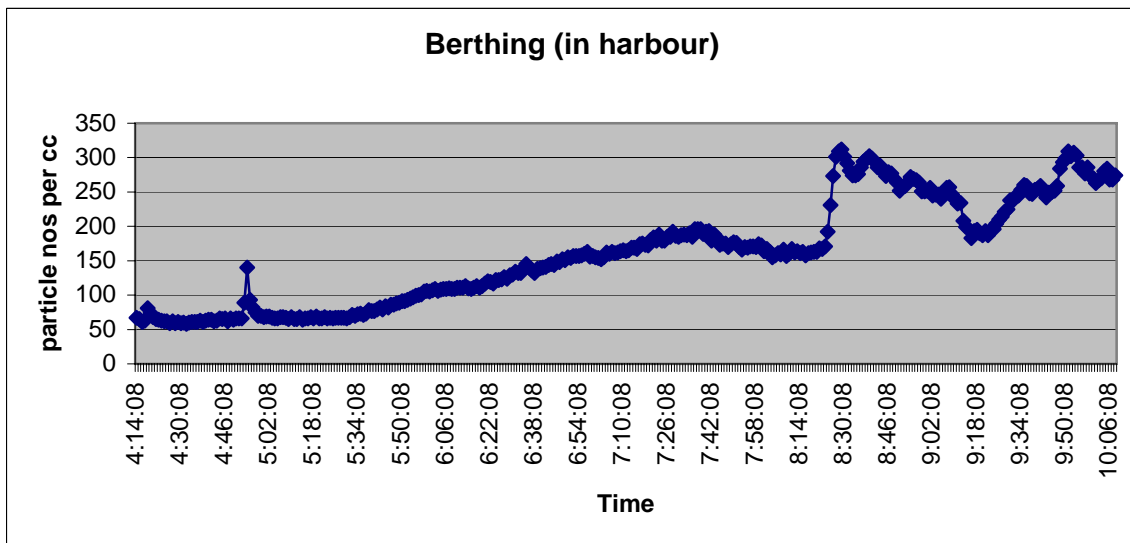


Figure 12. UFP measurements taken in the crews berthing while in port

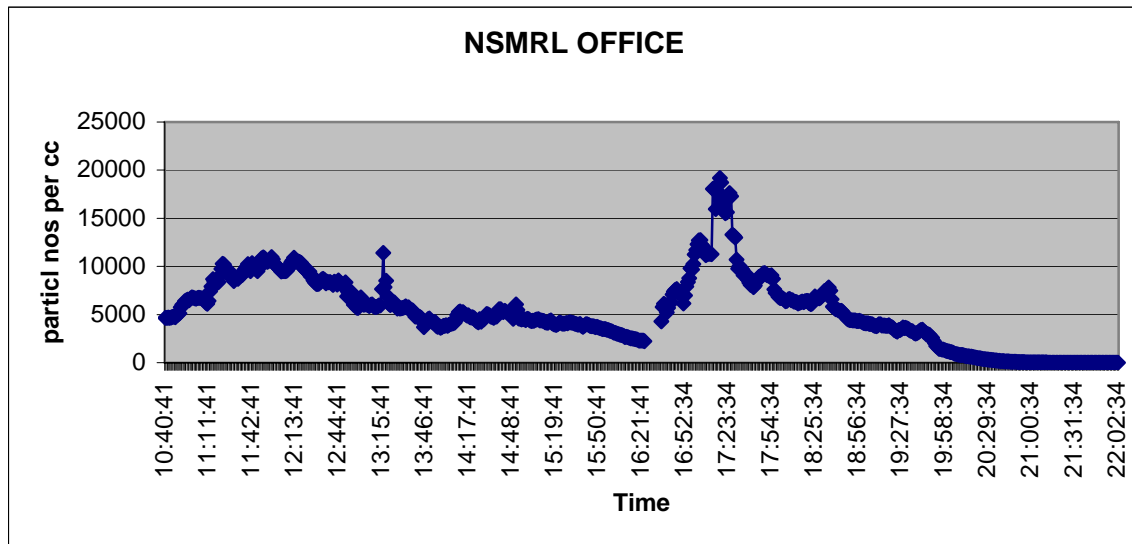


Figure 13. UFP measurements taken in NSMRL office

DISCUSSION

Prior to this study no attempt had been made to measure UFP in a submarine environment. The results obtained revealed that UFP numbers onboard operational submarines are low and comparable to, or less than, UFP numbers detected within office and residential spaces ashore. Within some compartments large variations in UFP numbers were noted; in the absence of a detailed minute-by-minute log of activity within the compartment these are difficult to explain. What is known is that the movement of persons within a space will disturb and put back into suspension UFP that have settled onto surfaces. This is clearly demonstrated in the measurements taken within the NSMRL office. Here it can be seen that the UFP levels have 2 peaks. The first is at midday when the office occupants were moving about preparing to leave the office for lunch, the second at the end of the working day when occupants were preparing to vacate the office. After the end of the working day when the office space was unmanned over approximately 2 hours the UFP numbers fell close to zero. A similar explanation can be suggested for the peaks that occur within some compartments during the onboard monitoring. One example is demonstrated by the UFP levels in the crew's lounge which show an increase commencing at 0020hrs, peaking at 0052hrs, correlating well with the time personnel coming off watch at midnight would pass through the crew's lounge to collect drinks, snacks and wind down before going to sleep. A similar pattern can be seen within the berthing area where UFP numbers, after remaining at a constant very low level (less than 100 particles/cm³) between 0414hrs and 0539hrs steadily increased as personnel woke, dressed and left the compartment for their duty station. Measurements taken within the galley reveal a low background count of between 500 to 1000 particles/cm³ until 2250hrs when a short-lived peak of 25,000 particles/cm³ was recorded. This correlates well with the time at which food preparation would occur for "mid rats"

(midnight meals and snacks) available for the on going watch keepers. Cooking is recognized to be a potent source of UFP with up to 590,000 particles/cm³ recorded in one study when bacon was cooked using a gas burner (12).

Explanation of the peaks noted within the control room are harder to explain, as they do not correlate with any obvious change in watch, but may be associated with the commencement of drills. During drills the number of personnel present and their activity level will increase. This would have the effect of disturbing UFP that had settled on surfaces and hence increase the number of UFP in suspension. In addition, during some drills, equipment, including ventilation fans and filter systems may be shut down.

The control room, crew's lounge, galley, berthing space and AMR are all situated within the forward compartment of the submarine which is where the majority of the crew work and all sleep and eat. The peak UFP count obtained in any of these spaces was 25,000 particles/cm³ which was recorded in the galley when it is assumed cooking was taking place. Excluding the peaks, scrutiny of the graphs reveals that for the majority of the time UFP numbers within the forward compartment of the submarine remained below 3,000 particles/cm³. Median values for the forward compartment range from a minimum of 161 particles/cm³ in the crew's berthing to a maximum of 2,692 particles/cm³ recorded in the galley while alongside. Wallace et al (5) measured UFP for a period of 18 months within a suburban house in the town of Reston, Virginia, reporting a mean UFP count of 2,370 particles/cm³ (SD \pm 3,940) during the time no UFP sources were present. The mean UFP count increased to 18,700 particles/cm³ (SD \pm 25,800) when UFP sources (defined as cooking and operation of the gas fired central forced air system) were present. Comparison between the figures obtained from a domestic property and those recorded within the forward compartment of an operational submarine, reveal that a submariner's UFP exposure during off watch time and during watch keeping within the forward compartment is similar to, or less than, their exposure would be within a small suburban house.

UFP measurements were also recorded within the aft compartment of the submarine, which is where all the heavy machinery concerned with power generation and propulsion is situated. Particle counts in this area were higher than those measured forward but even here UFP numbers were still relatively low. Measurements taken when the submarine was in port (median 10,441 particles/cm³) and then when first at sea (median 5,750 particles/cm³), reveal remarkably constant UFP numbers. Recordings taken after 20 days at sea reveal a step change in UFP count at 0853, when UFP numbers increase from approximately 5,000 particles/cm³ to 35,000 particles/cm³ for the remainder of the recording period. The most probable reasons for this large increase in UFP numbers are either the commencement of some drill during which ventilation and air filter systems may have been shut down, or possibly the start of a cleaning period during which dust, including UFP, would have been disturbed and put back in suspension. In the absence of a detailed minute-by-minute log of the submarine's activities during the data collection, it is impossible to determine the precise cause of this marked increase in UFP.

Although UFP numbers were higher in the aft compartment than the forward compartment, the numbers were still relatively low when compared to measurements that have been taken in various European and US towns and cities. Osunsanya et al (6) reported a median value of 10,241 particles/cm³ in the City Centre of Aberdeen, Scotland, while Penttinen et al (13) reported a median value of 14,500 particles/cm³ in the town of Kuopio, Finland. Finally, Zhu et al (7) reported a range of UFP from a minimum of 130,000 to a maximum of 200,000 particles/cm³ at a site 30 meters from Interstate 405 in Los Angeles, California. Even these figures are low compared to figure of 590,000 particles/cm³ recorded by Dennekamp et al (11) when frying bacon using a gas burner. It should be noted that although the gas burner contributed to the UFP production, frying bacon using an electric ring still generated 159,000 particles/cm³.

In both the control room, and maneuvering, there is a suggestion that UFP numbers actually decrease while the submarine is underway. However, it must be noted that the differences between the initial and +20 days at sea median values are small, and when combined with the unexplained peaks recorded it is not possible to determine with accuracy whether or not this is a significant finding. What is encouraging is that the trend appears to be downward, with no evidence of a significant increase in UFP while underway. This suggests that either few UFP are being generated by submarine onboard equipment and/or that the existing atmosphere filtering systems are highly efficient at removing UFP from the submarine atmosphere. Another possibility is that respirable oil mist, known to be present in the submarine machinery spaces, may act as a condensation nuclei collector for UFP.

CONCLUSIONS

This study confirmed the TSI P-TRAK™ Ultra Fine Particle Counter Model 8525 to be a reliable and robust device capable of measuring and recording UFP numbers within the challenging environment that is an operational submarine.

The study also reveals that UFP, although present in the submarine environment, are not at levels that are likely to constitute a hazard to the health of submariners. UFP numbers in the forward compartment of the submarine are comparable to the levels recorded within a small suburban house. In the aft compartment the levels of UFP are higher but even here no greater than, indeed probably considerably less than, would be experienced by an individual who worked in a city center and who commuting to work by car. Thus a submariner whose duty station is in the forward compartment is probably exposed to far fewer UFP while underway than he would be if employed ashore in a non-industrial occupation. Even the submariner whose duty station is in the machinery spaces in the aft compartment is probably exposed to less UFP than if he worked in a city centre and lived in the suburbs.

UFP numbers may actually decrease during the time a submarine is underway although the data collected is not sufficiently robust to categorically state this.

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